EFFECT OF STATIC SHEAR STRESS ON UNDRAINED CYCLIC BEHAVIOR OF SATURATED SAND

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ABSTRACT: To investigate the effect of static shear stress on the undrained cyclic behavior of saturated sand, a series of torsional shear tests was conducted on saturated Toyoura sand specimens up to extremely large strain level of about 100%. After being isotropically consolidated, the specimens were subjected to drained monotonic torsional shear stress, and then, undrained cyclic torsional shear stress was applied. The amplitude of combined static and cyclic shear stress was kept constant by correcting the measured value for the effect of membrane force. The test results revealed that the effective stress path and the stress-strain curve during the cyclic shear loading were affected by the initial static shear stress. Accumulation of shear strain was clearly noticed in the same direction where previously static shear stress was applied. Progressive localization of specimen deformation was observed.

Key Words: Large strain, Liquefaction, Membrane force, Sand, Static shear stress, Torsional shear test

INTRODUCTION

Extremely large deformations could be observed on liquefied gentle slope of sand, following earthquake events, such as the 1964 Niigata and 1983 Nihonkai-Chubu earthquakes (Hamada et al., 1994). Even though the gradient of slopes was merely of some percents, their lateral spreading achieved several meters. Due to liquefaction, flow of slope can occur when the mobilized shear stress of soil in its liquefied state exceeds the shear stress required for the static equilibrium of soil mass. Once deformations produced by flow liquefaction are triggered, they may become extremely large depending on the acting static shear stress.

Many laboratory tests under different conditions (in term of density, confining pressure, stress ratio, severity of liquefaction, etc…) have shown that large deformation always occurs after liquefaction of sand, and it can be developed when the effective mean principal stress in sand momentarily achieves zero state during undrained loading (e.g., Koseki et al., 2005 and 2007; Kiyota et al. 2008). These cyclic torsional or triaxial tests were carried out on isotropically consolidated specimens, in which there is no static shear stress; this zero static stress state represents the stress conditions of level ground.

Towhata (2008), regarding the effects of initial static shear stress combined with cyclic torsional shear stress, pointed out that in case of one-way loading (the shear stress is always positive), the specimen maintained its stability and liquefaction was not achieved. In case of two-way loading the

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specimen easily liquefied and developed large shear deformation. However, due to mechanical limitation of the employed apparatus the shear strain level could not exceed 10%.

On the other hand, Yasuda et al. (1992), by conducting shaking table tests with different sloping ground surface and thickness of liquefied sand layer, showed that permanent ground displacement would not occur along any specific surface of rupture, but would occur throughout a liquefied layer because of a fall of shear strength and shear modulus due to liquefaction.

Since the soil in a sloping ground is always subjected to an initial driving shear stress prior to seismic loading, and because properties of liquefied soil under extremely large deformation are not understood well, in the present study, in order to investigate the effect of initial static shear stress level on the undrained cyclic behavior of saturated Toyoura sand, a series of undrained cyclic torsional shear tests was performed up to a double amplitude of shear strain of about 100%.

TEST APPARATUS

To achieve extremely large torsional shear displacements, a fully automated torque loading device on hollow cylindrical specimens (Fig. 1), developed by Koseki et al. (2007) and Kiyota et al. (2008), was employed in this study.

It is capable of achieving double amplitude torsional shear strain levels exceeding 100% by using a belt-driven torsional loading system that is connected to an AC servo motor through electro-magnetic clutches and reduction gears.

To evaluate large torsional deformations, a potentiometer with a wire and a pulley was employed, as illustrated in Figs. 1b) and 1c). The torque and axial load were detected by using a two-component load cell which is installed inside the pressure cell.

The hollow cylindrical specimen was 150mm in outer diameter, 90mm in inner diameter and 300mm in height.

TEST PROCEDURE

The material employed in this study was Toyoura sand, a uniform sand with negligible fines content under 75μm (Table 1). Several specimens, as listed in Table 2, were prepared by pluviation air-dried sand particles through air. Their initial relative density of about 43% was obtained by using a funnel and keeping constant the height of pluviation. After saturating the specimens with pouring carbon dioxide and then pouring de-aired water, they were isotropically consolidated by increasing the effective stress state up to 100kPa, with a back pressure of 200kPa. Subsequently, the stress state was changed by applying drained monotonic torsional shear stress up a specified value. Finally, undrained cyclic torsional loading, with constant double amplitude of shear stress of 32kPa, was applied at a constant shear strain rate of 2.5 %/min. The loading direction was reversed when the amplitude of combined shear stress, which was corrected for the effect of membrane force, reached the target value. For all the duration of torsional loading, both monotonic and cyclic cases, the vertical deformation of the specimen was kept to be zero by using a mechanical locking devices for the vertical displacement of loading shaft.

Table 1 Material properties

Material	Specific gravity, G_s	Maximum void ratio, e_{max}	Minimum void ratio, e_{min}	Mean diameter, D_{50} (mm)	Fines content, F_C (%)
Toyoura sand	2.656	0.992	0.632	0.16	0.1

Table 2 Test conditions

Test	Relative density, D_r	Static Shear Stress, τ_S	Combined static and cyclic shear stress, $\tau=\tau_S \pm \tau_{CL}$	Type of loading
Test SH05	43.3%	5kPa	+21 / -11kPa	Two-way
Test SH10	44.3%	10kPa	+ 26 / -6kPa	Two-way
Test SH15	41.9%	15kPa	+ 31 / -1kPa	Two-way
Test SH20	43.2%	20kPa	+36 / +4kPa	One-way

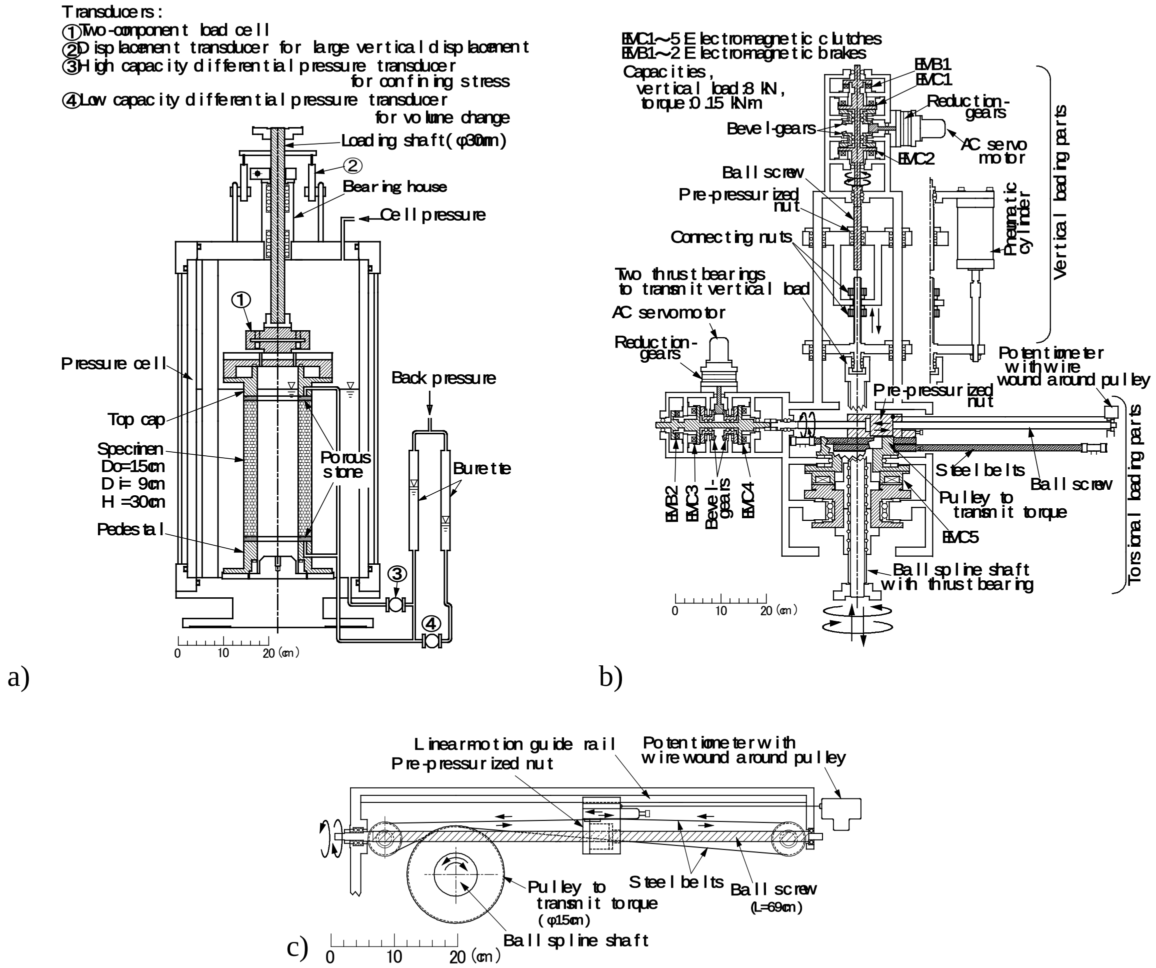


Figure 1 a) Torsional shear test apparatus on hollow cylindrical specimen; b) loading device and c) plan view of torque-transmission part.

TEST RESULTS

Correction for membrane force

As Koseki et al. (2005 and 2007) among others pointed out, in torsional shear tests on hollow cylindrical specimen due to the presence of inner and outer membranes, the effect of membrane force can not be neglected. Furthermore, it becomes significantly important when shear strain reach extremely high level as Kiyota et al. (2008) indicated.

Usually, the membrane force has been corrected based on the linear elasticity theory, which uses the Young's modulus of the membrane. The theoretical apparent shear stress, τ_m, induced by the inner and the outer membranes can be evaluated as:

$$\tau_m = \frac{t_m\, E_m \left(r_o^3 + r_i^3\right)\theta}{\left(r_o^3 - r_i^3\right)h} \tag{1}$$

where θ is the rotational angle of the top cap detected by external potentiometer; h is the height of the specimen; r_o and r_i are the outer and inner radii of the specimen; t_m and E_m are, respectively, the thickness (=0.3 mm) and the Young's modulus (=1492 kPa) of the membrane.

In order to confirm the validity of Eq. (1) in correcting for effect of membrane force, a special test was performed by filling water between the inner and outer membranes and shearing it cyclically under undrained condition up to single amplitude shear strain of 50% (Photo 1).

Figure 2 shows both experimental and theoretical relationships between shear strain and apparent shear stress that is induced by the membranes due to torsional deformation. As expected, the deviation of the actual membrane deformation from the uniform one that is assumed in the theory became larger with increase in the strain level. Hence, in this study, the shear stress was corrected for the effect of membrane force by employing the polynomial approximation of the measured relationship between γ and τ_m as shown in Fig. 2.

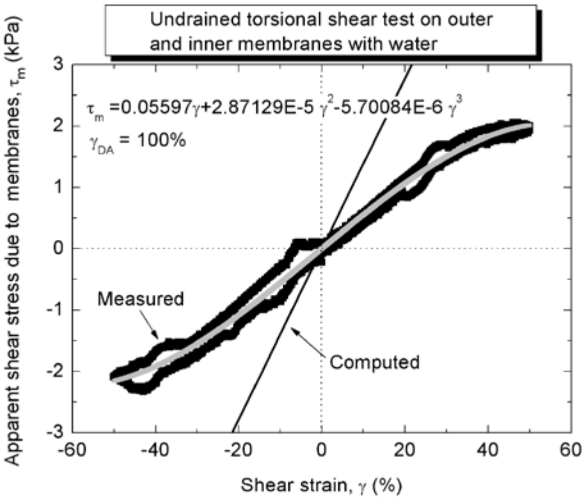


Figure 2 Relationships between apparent shear stress due to membrane force and shear strain

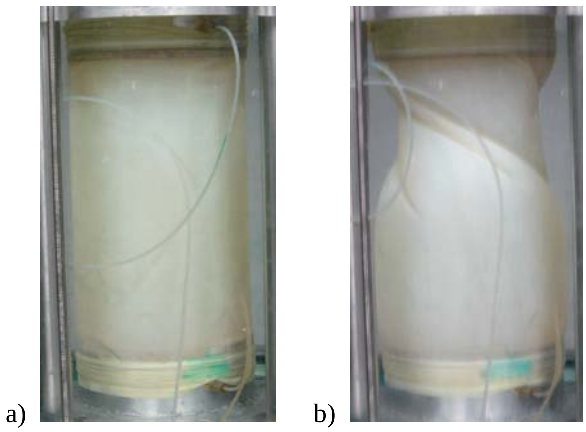
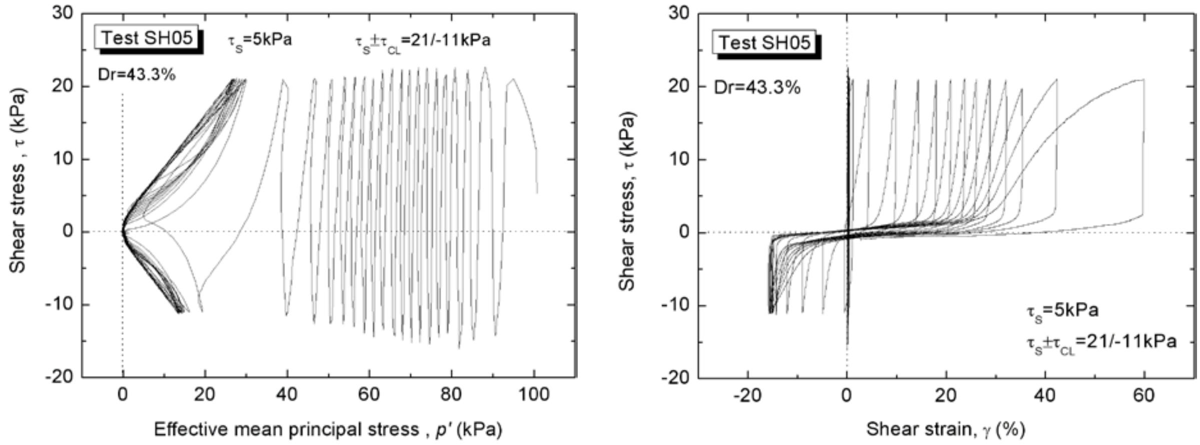


Photo 1 Deformation of water specimen: a) before test (γ=0%) and b) at γ=50%

Two-way loading test results

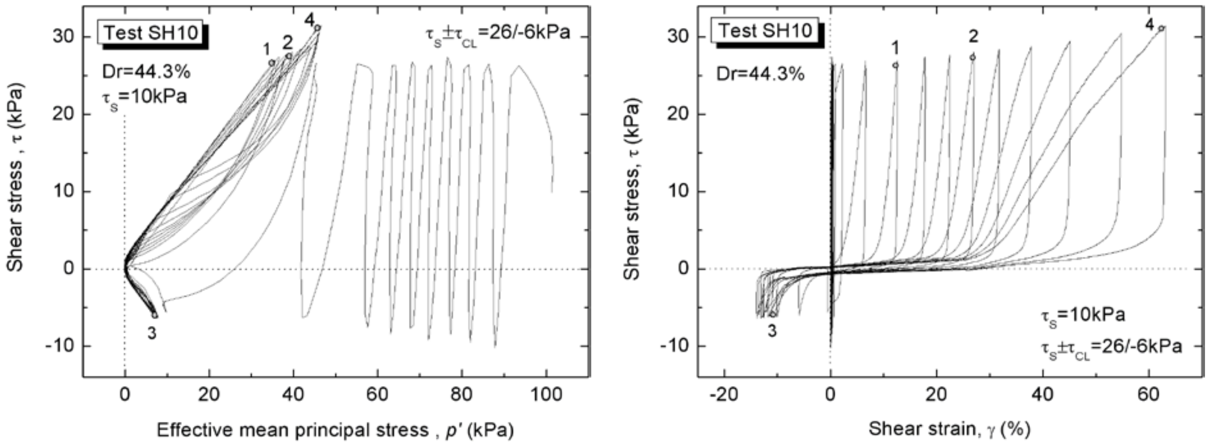
During each cycle of loading in some tests, the combined static and cyclic shear stress value is reversed from positive ($\tau = \tau_S + \tau_{CL} > 0$) to negative ($\tau = \tau_S - \tau_{CL} < 0$), or vice versa; this type of loading will be called hereafter as two-way loading.

Typical two-way loading test results on Toyoura sand specimens, in which static shear stress with magnitude of 5, 10 and 15kPa, respectively, was applied before undrained torsional loading, are shown in Figs. 3, 4 and 5.



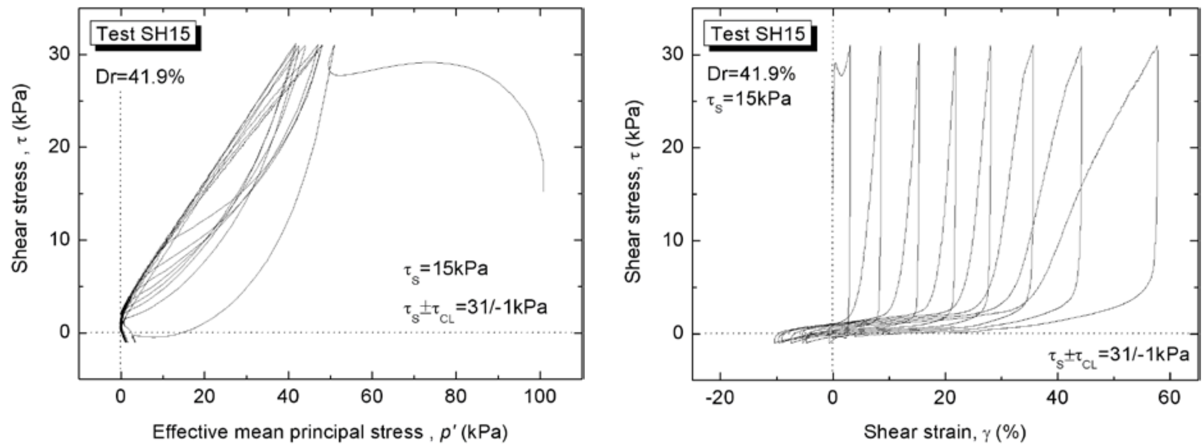
a) effective stress path
b) stress-strain relationship

Figure 3 Typical test result on Toyoura sand applying static shear stress (τ_S=5kPa)



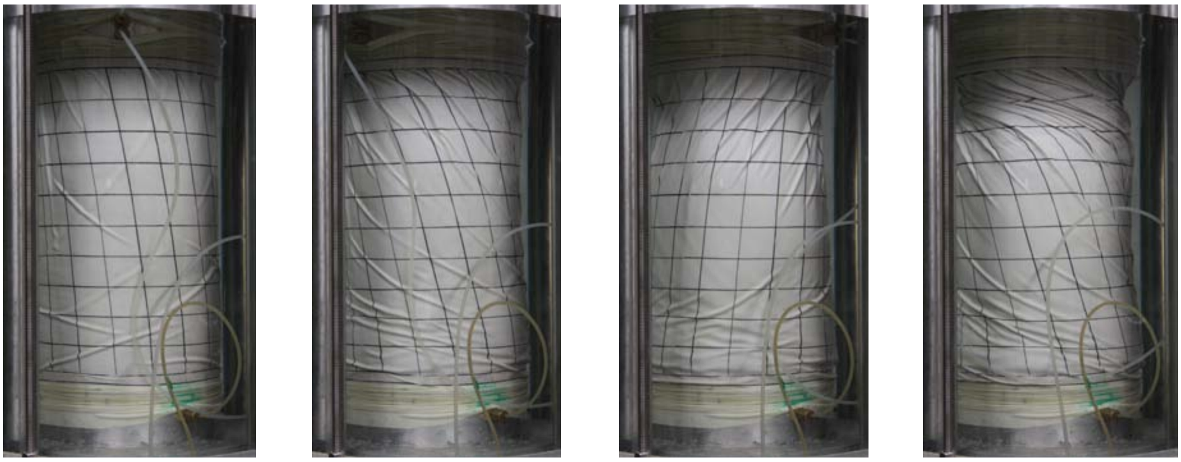
a) effective stress path
b) stress-strain relationship

Figure 4 Typical test result on Toyoura sand applying static shear stress (τ_S=10kPa)



a) effective stress path
b) stress-strain relationship

Figure 5 Typical test result on Toyoura sand applying static shear stress (τ_S=15kPa)



a) state 1 (γ=12%) b) state 2 (γ=27%) c) state 3 (γ=-11%) d) state 4 (γ=63%)

Photo 2 Specimen deformation at states 1 through 4 shown in Fig. 4

The cyclic mobility was observed in Figs. 3a), 4a) and 5a) where the effective stress recovered repeatedly after achieving the state of zero effective stress (i.e., liquefaction). It was accompanied with a significant development of double amplitude shear strain, γ_{DA}, as shown in Figs. 3b), 4b) and 5b).

It was found that the pre-liquefaction behavior of saturated sand was affected by the amount of static shear stress, (e.g., number of cycles to cause liquefaction decreased with the increase in the static shear stress). It should be noted that significant shear strain was induced when the effective stress became almost 40% of the initial effective stress level before dropping suddenly to the zero effective stress state. In the post-liquefaction state, the shear strain increased with the number of cycles; this process clearly depended on the applied static shear stress, in the sense that accumulation of shear strain was noticed in the same direction where the previously monotonic drained shear stress was applied.

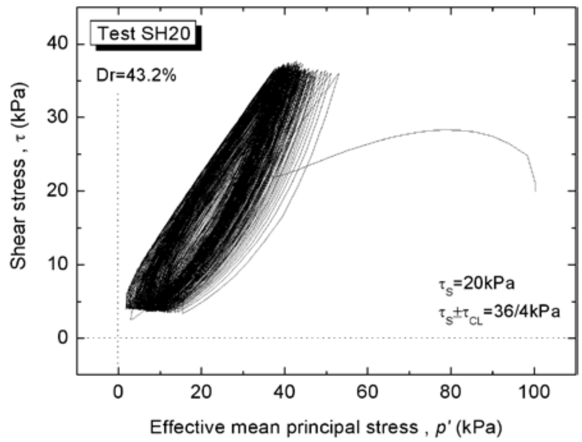
Specimen deformation at several states as numbered 1 through 4 in Fig. 4 is shown in Photo 2. At state 1 (γ= 12%), the deformation was almost uniform except for the regions close to the pedestal and the top cap that are affected by the end restraint; the outer membrane appeared slightly wrinkled. At state 2 (γ= 27%), the outer membrane was visibly wrinkled; in the region near the top cap the deformation of the specimen started to localize due to water film formation. At state 3 (γ=-11%), the localization of specimen deformation developed clearly in the upper part of the specimen. At state 4 (γ=63%), the specimen was almost twisted near the top cap.

One-way loading test results

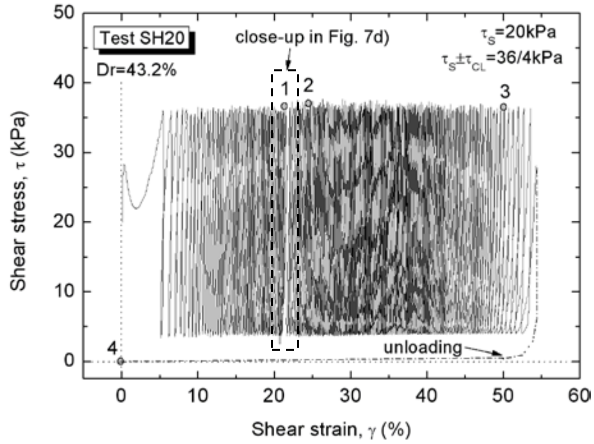
The type of loading in which the combined shear stress (static + cyclic, $\tau_S \pm \tau_{CL}$) is always positive or achieves zero state momentarily during the undrained torsional shear loading, is herein called one-way loading.

Fig. 6 shows test results with one-way loading. As indicated in Fig 6a), the state of zero effective stress was not reached even after applying 208 cycles. Figs. 6b) and c) show that a large shear strain level exceeding 50% was achieved, even though cyclic mobility did not occur.

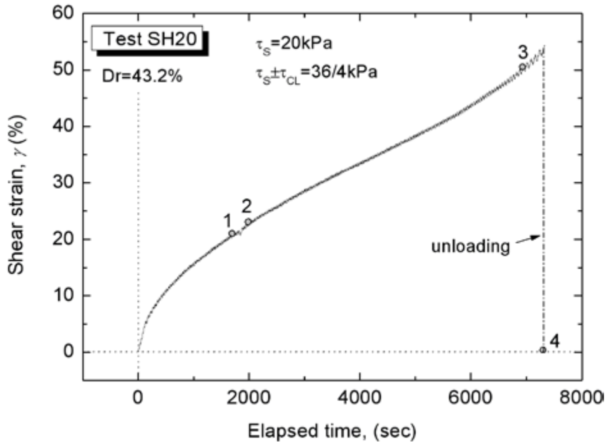
In addition, a peculiar behavior of Toyoura sand under cyclic torsional loading was observed once the shear strain achieved a level of about 21%. In Fig. 6d) a drop of shear stress exceeding the target value of control could be observed. Also the shear strain suddenly shifted of same percents, Figs. 6b), c) and d).



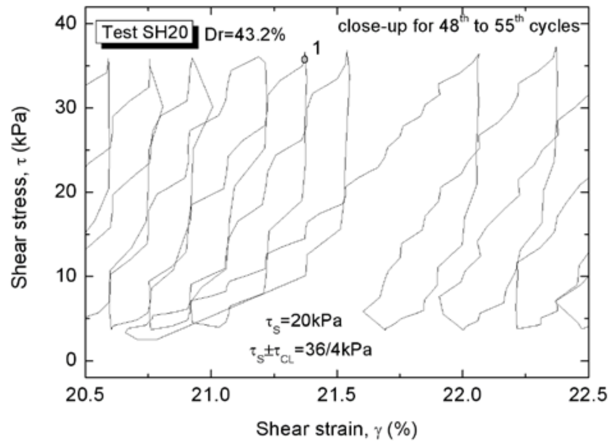
a) effective stress path



b) stress-strain relationship



c) time history of shear strain



d) close-up of stress-strain relationship

Figure6 Typical test result on Toyoura sand applying static shear stress (τ_S=20kPa)

a) state 1 (γ=21%)

b) state 2 (γ=25%)

c) state 3 (γ=50%)

d) state 4 (after test)

Photo 3 Specimen deformation at states 1 through 3 shown in Fig. 6

Specimen deformation at several states as numbered 1 through 4 in Fig. 6 is shown in Photo 3. The sequence of state 1 (γ=21%) and state 2 (γ=25%) shows specimen deformation before and after the above described phenomenon.

At state 1 (γ=21%) the deformation was rather uniform except for the zones near the top cap and pedestal due to the effect of end restraint. At state 2 (γ=25%) the outer membrane was wrinkled at several locations due to local drainage. At state 3 (γ=50%) the membrane was extensively wrinkled from the bottom to the top. At state 4 (after test), when zero shear strain state was recovered while keeping undrained condition, formation of a spiral shear band could be observed (Photo 3d).

The results of this one-way loading test indicate that, when the combined shear stress can not reach zero state, liquefaction (i.e., the zero effective stress state) does not occur. However, this does not mean that sand is very resistant against seismic loading, in fact a significant magnitude of combined shear stress may cause failure as evidenced with the formation of shear band.

CONCLUSIONS

Since the soil in a sloping ground is always subjected to an initial driving shear stress prior seismic loading, in order to investigate the effect of static shear stress on the cyclic behavior of liquefied sand, a series of undrained cyclic torsional shear tests was conducted on saturated Toyoura sand specimens up to extremely large deformation. From the present study, analyses of test results revealed that:

a) by employing the modified torque loading devices undrained cyclic torsional tests could be conducted on saturated Toyoura sand up to double amplitude of about 100%;
b) in using hollow specimens, due to the presence of inner and outer membranes, correction for effect of membrane force on the measured value of shear stress is indispensable;
c) saturated loose Toyoura sand undergoing cyclic torsional shear stress behaved in two different ways depending on the value of combined shear stress (static + cyclic). In case of two-way loading, the sand easily liquefied and large deformation was developed while showing cyclic mobility. On the other hand, in case of one-way loading, liquefaction did not occur, while under large shear strain levels formation of shear bands was clearly observed;
d) both the effective stress path and the stress-strain curve were affected by the initial static shear stress level. In particular, two-way loading tests revealed that, by increasing the initial amount of static shear stress, large shear strain levels could be achieved by applying less cycles;
e) accumulation of shear strain was clearly noticed in the same direction where previously monotonic drained shear stress was applied;
f) under extremely large strain level localization of specimen deformation was also observed. In two-way loading tests, they were visible in the region near the top cap where the specimen was almost twisted due to water film formation; whereas, in case of one-way loading, due to local drainage the outer membrane was extensively wrinkled along the whole specimen height.

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